Pion Decay-at-Rest Neutrino Sources for Precision Studies of the Standard 3x3 Neutrino Paradigm

Snowmass Workshop on Frontier Capability
Brookhaven National Lab

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Georgia Karagiorgi, Columbia U.

(Two of) Outstanding Questions in Neutrino Physics

1. CP violation

Potential CP-violation in the lepton sector is accessible through three-neutrino mixing:

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \times \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \times \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$c_{ij} \equiv \cos\theta_{ij}$$
$$s_{ij} \equiv \sin\theta_{ij}$$

δ_{CP} : Fundamentally significant parameter:

1) Last remaining unknown parameter in standard 3x3 neutrino mixing
2) Related to matter-antimatter asymmetry via neutrino mass models and Leptogenesis

We need to measure this!

(Two of) Outstanding Questions in Neutrino Physics

1. CP violation

2. Sterile neutrinos

Additional, non-weakly interacting neutrino species which may be responsible for several "short-baseline anomalies"

Several experimental hints of oscillations through sterile neutrino state with $\Delta m^2 \approx 1\ eV^2$:

- LSND / MiniBooNE ν_e / $\bar{\nu}_e$ appearance
- Reactor $\bar{\nu}_e$ disappearance ("Reactor Anomaly")
- Radioactive source ν_e disappearance
- But still no indication of ν_μ disappearance

Establishing the existence of sterile neutrinos would be a major result for particle physics, but need definitive experiments

We need to address this!

(Two of) Outstanding Questions in Neutrino Physics

1. CP violation

2. Sterile neutrinos

↓

High-precision measurements:

Oscillation probability differences of O(1%)

→ need large detector(s), high intensity beam(s), and controlled systematics.

Needs are especially challenging for CP violation search.

↓

Step 1: Sterile neutrino (short baseline) oscillations: IsoDAR

Step 2: CP-violating (long baseline) oscillations: DAEδALUS

Higher beam intensity needs: Requires R&D → Future

Searching for CP violation ($\delta_{CP} \neq 0$)

$\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e$ oscillations at 2π E/L ≈ $|\Delta m^2_{31}|$ are sensitive to δ_{CP}

Vacuum oscillation probability:

$$
\begin{aligned}
P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e) = \; & (\sin^2\theta_{23} \sin^2\theta_{13}) (\sin^2\Delta_{31}) \\
& -/+ \; \sin\delta_{CP} (\sin2\theta_{13} \sin2\theta_{23} \sin2\theta_{12}) (\sin^2\Delta_{31}\sin\Delta_{21}) \\
& + \cos\delta_{CP} (\sin2\theta_{13} \sin2\theta_{23} \sin2\theta_{12}) (\sin\Delta_{31} \cos\Delta_{31} \sin\Delta_{21}) \\
& + \underbrace{(\cos^2\theta_{23} \sin^2\theta_{12})}_{\text{terms depending on mixing angles}} \underbrace{(\sin^2\Delta_{21})}_{\text{terms depending on mass splittings}}
\end{aligned}
$$

We want to see if $\delta_{CP} \neq 0$

$$\Delta_{ij} = 1.27 \, \Delta m_{ij}^2 \, L[m]/E_\nu[MeV]$$

Searching for CP violation ($\delta_{CP} \neq 0$)

DAEδALUS approach: Use L/E-dependence of P($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$) to extract δ_{CP}

Vacuum oscillation probability:

$$
\begin{aligned}
P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = \quad & (\sin^2\theta_{23} \sin^2\theta_{13})\,(\sin^2\Delta_{31}) \\
& - \sin\delta_{CP}\,(\sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12})\,(\sin^2\Delta_{31} \sin\Delta_{21}) \\
& + \cos\delta_{CP}\,(\sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12})\,(\sin\Delta_{31} \cos\Delta_{31} \sin\Delta_{21}) \\
& + \underbrace{(\cos^2\theta_{23} \sin^2\theta_{12})}_{\text{terms depending on mixing angles}}\,\underbrace{(\sin^2\Delta_{21})}_{\text{terms depending on mass splittings}}
\end{aligned}
$$

We want to see if $\delta_{CP} \neq 0$

$$\Delta_{ij} = 1.27\,\Delta m_{ij}^2\,L[m]/E_\nu[MeV]$$

Searching for CP violation ($\delta_{CP} \neq 0$)

Traditional approach to $\overset{(-)}{\nu}_e$ appearance:

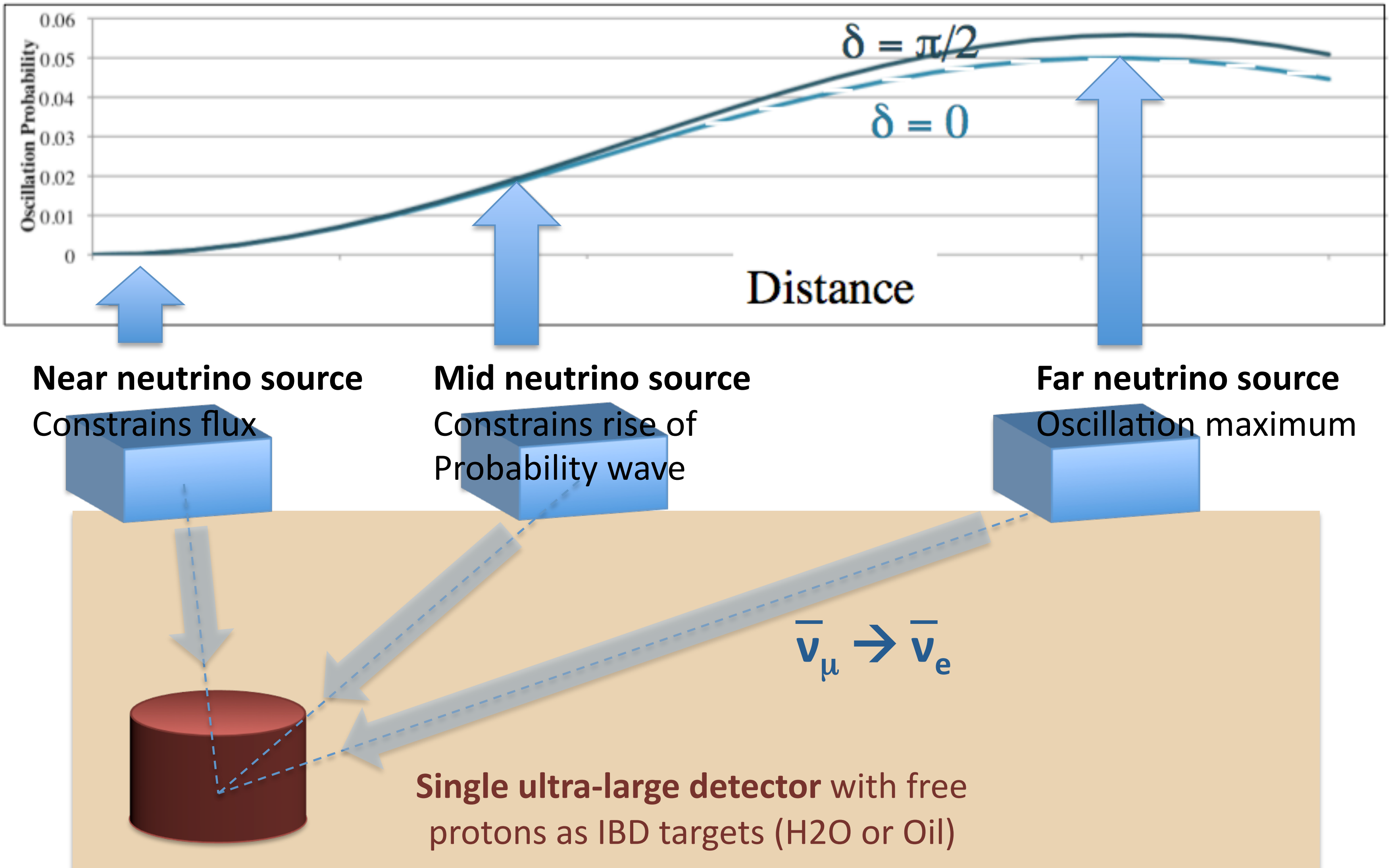
<u>**Single**</u> neutrino source + <u>**multiple**</u> neutrino detectors at different baselines

DAEδALUS approach to $\bar{\nu}_e$ appearance:

<u>**Multiple**</u> neutrino sources at different baselines + <u>**single**</u> neutrino detector

* *J.M Conrad and M. H. Shaevitz, PRL 104, 141802 (2010)*

DAEδALUS Search for CP violation ($\delta_{CP} \neq 0$)



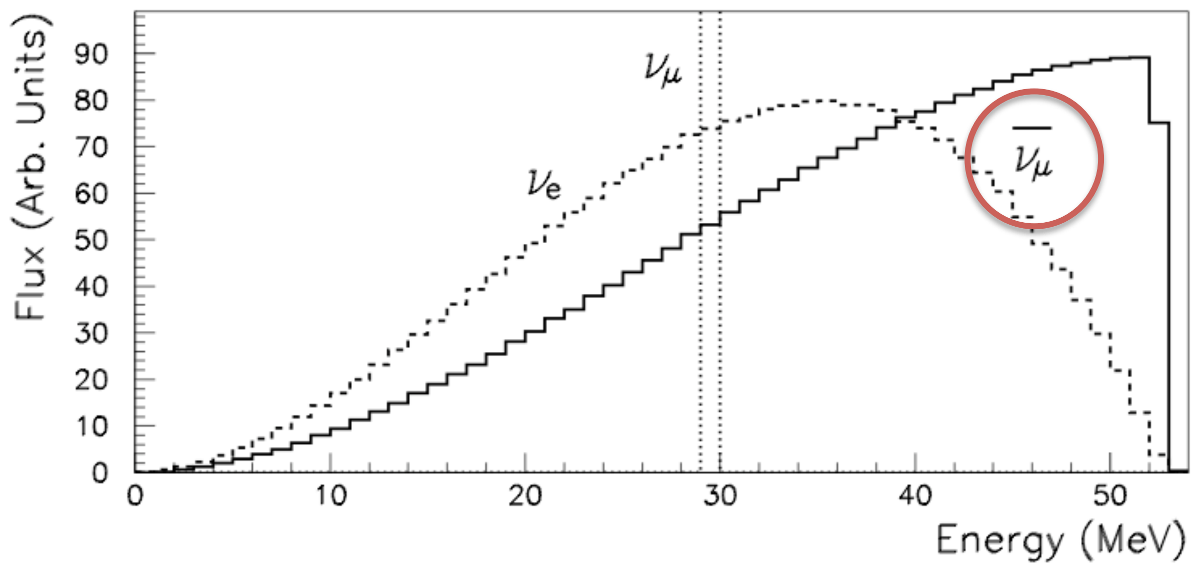
DAEδALUS Antineutrino Source(s)

π^+ Decay-at-Rest (DAR) neutrino source:

$$p + C \rightarrow \Delta \rightarrow \pi^+ \rightarrow \mu^+ \nu_\mu$$

$$\mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e$$

Beam $\bar{\nu}_e$ contribution (π^- decay) is insignificant: 0.01 %



A great place to look for:

$\boxed{\bar{\nu}_\mu \rightarrow \bar{\nu}_e}$

Weak process: shape driven by nature and well-predicted
Only normalization varies from source to source

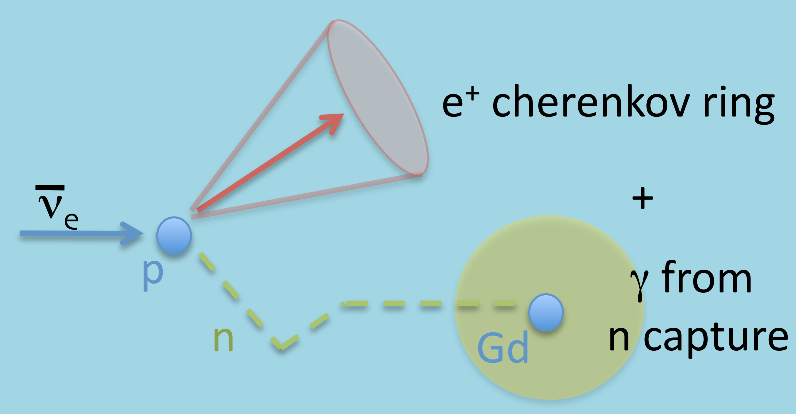
DAEδALUS Detector

Oscillation signal: IBD excess

Look for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
via **inverse beta decay (IBD)**:

$\bar{\nu}_e + p \rightarrow n + e^+$

IBD signature: delayed coincidence



Ideal process for appearance signal:

1. Well-known cross section (<1%)
2. Large cross section
3. Neutrino energy reconstruction
4. Delayed coincidence

Requires free protons for neutron tagging:

✓ Gd-doped water cherenkov
✓ Scintillator detector
✗ Liquid Argon TPC

Measurement Strategy

Using the **near** neutrino source
measure **absolute flux normalization** with ν_e-e events to ~1%,
Also, measure the ν_eC (ν_eO) event rate.

At far and mid-distance neutrino source,
Compare predicted to measured ν_eC (ν_eO) event rates
to get the **relative flux normalizations between 3 sites**

For all three neutrino sources,
given the known flux, **fit for the $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ signal**
with δ as a free parameter

Beam requirements (I)

High power beam → High signal event statistics

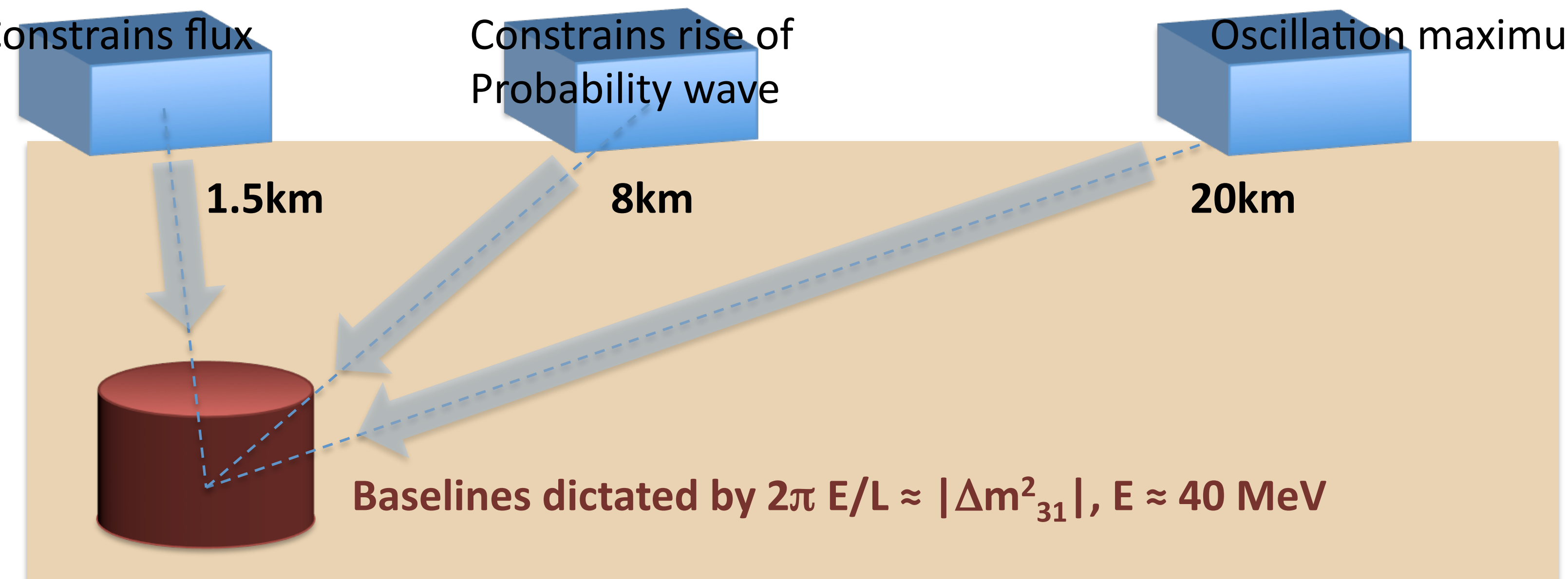
Need: ~4E22 $\bar{\nu}_\mu$/accelerator/year

Beam power ratio optimized for physics given isotropic flux dependence:
Near:Mid:Far ~ 1:2:5

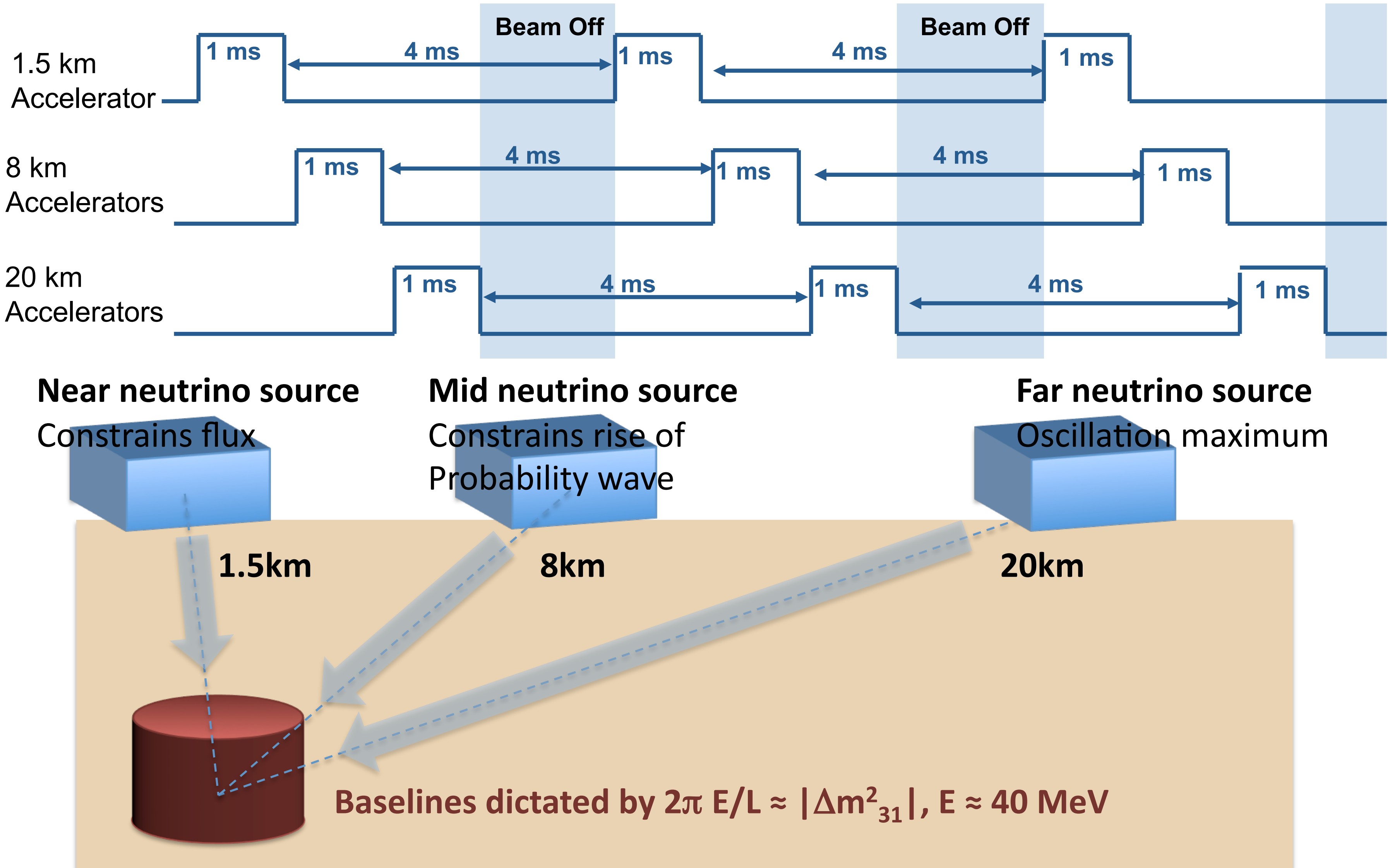
Near neutrino source
Constrains flux

Mid neutrino source
Constrains rise of
Probability wave

Far neutrino source
Oscillation maximum



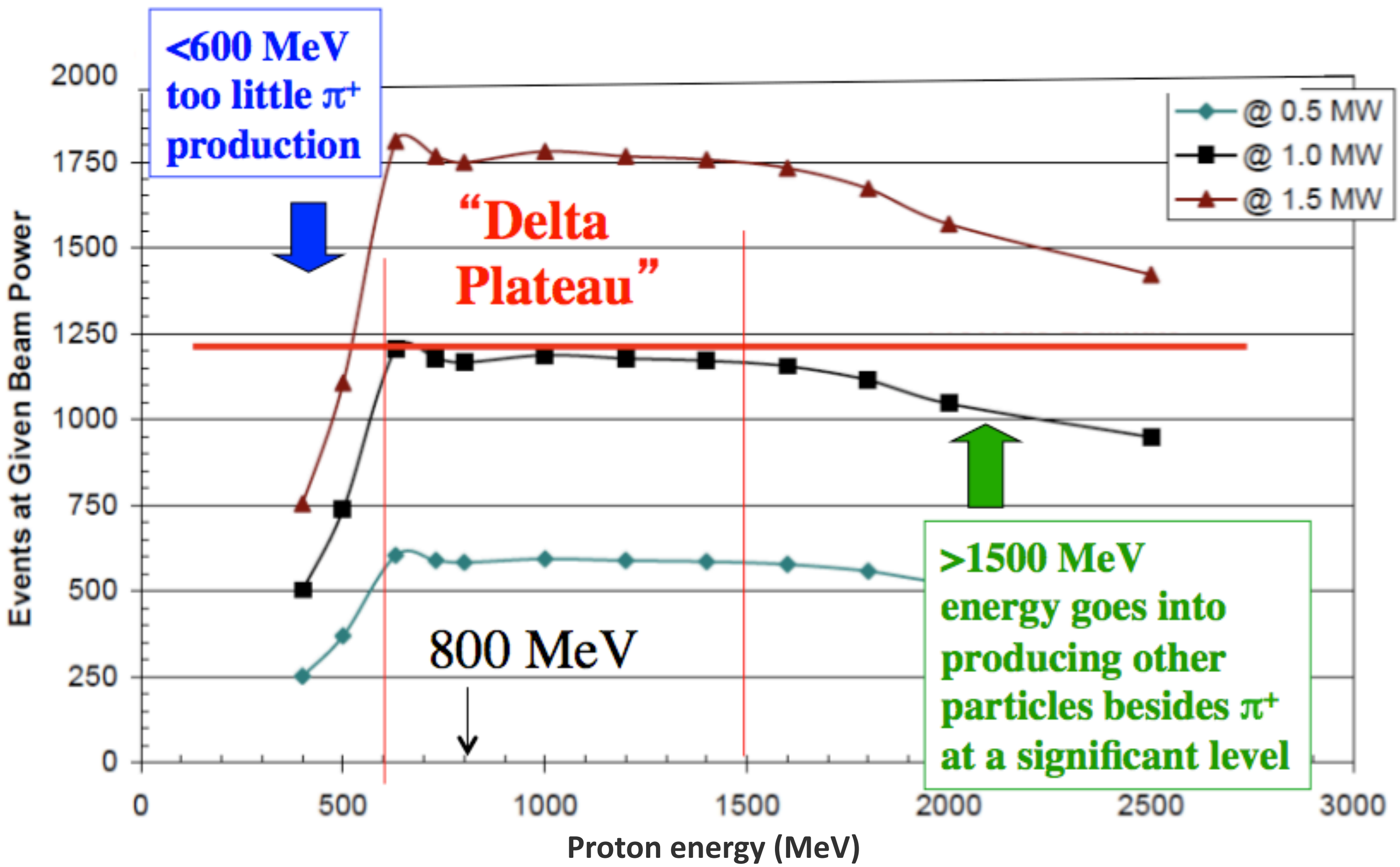
Beam requirements (II)



Beam requirements (III)

What proton energy is required?

There is a "Delta plateau" where one can trade energy for current to get the same rate of ν/MW

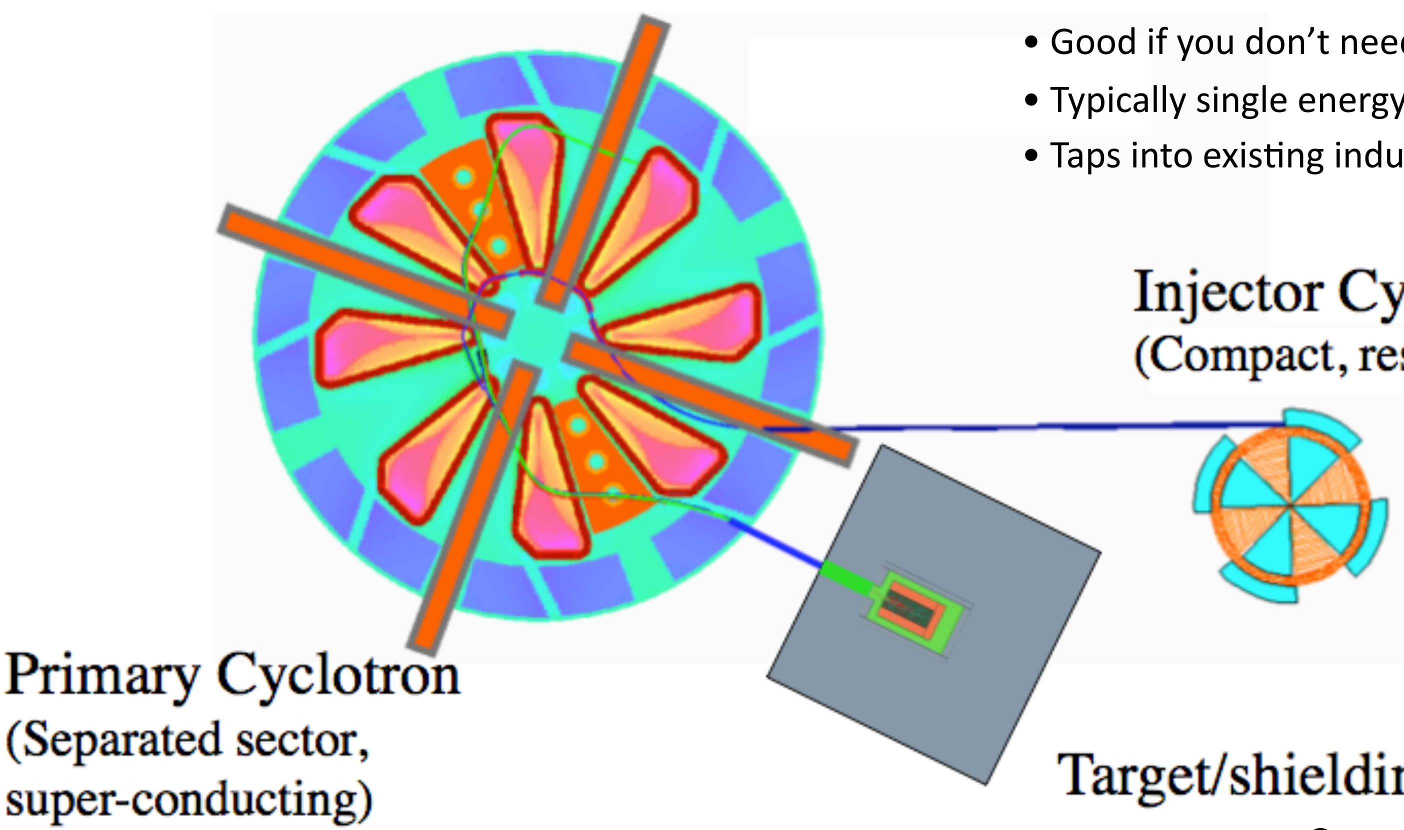


800 MeV Protons from Cyclotrons

DAEdALUS uses multiple "Accelerator Units" to produce its DAR beam, constructed out of Cyclotrons:

Motivation for technology choice:

- Inexpensive,
- Practical below ~1 GeV
- Good if you don't need short timing structure
- Typically single energy
- Taps into existing industry



See talk by J. Alonso

Strong R&D Effort within Collaboration

arXiv.org > physics > arXiv:1207.4895

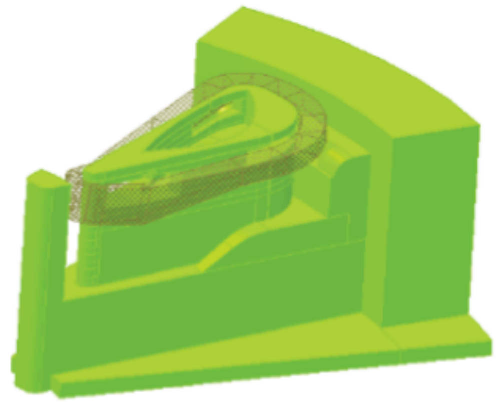
Physics > Accelerator Physics

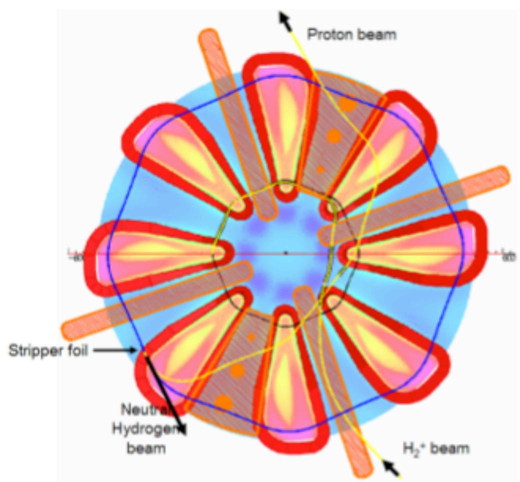
Multimegawatt DAEδALUS Cyclotrons for Neutrino Physics

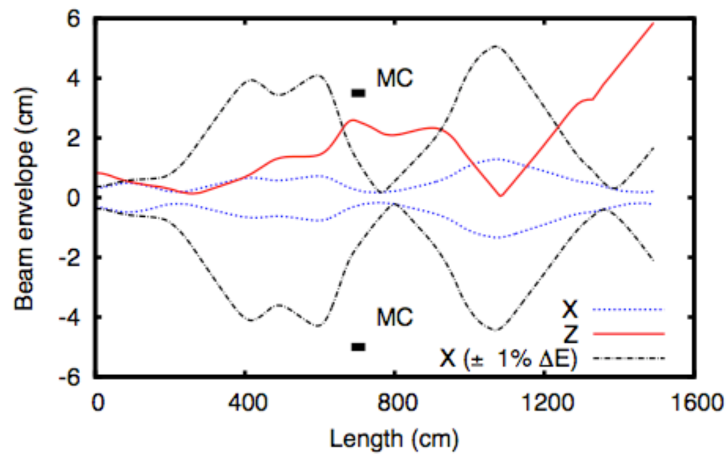
M. Abs[j], A. Adelmann[b,*], J.R. Alonso[c], W.A. Barletta[c], R. Barlow[h], L. Calabretta[f], A. Calanna[c], D. Campo[c], L. Celona[f], J.M. Conrad[c], S. Gammino[f], W. Kleeven[j], T. Koeth[a], M. Maggiore[e], H. Okuno[g], L.A.C. Piazza[e], M. Seidel[b], M. H. Shaevitz[d], L. Stingelin[b], J. J. Yang[c], J. Yeck[i]

[a]Institute for Research in Electronics and Applied Physics, University of Maryland, College Park, Maryland, 20742
[b]Paul Scherrer Institut, CH-5234 Villigen, Switzerland
[c]Department of Physics, Massachusetts Institute of Technology
[d]Columbia University
[e]Istituto Nazionale di Fisica Nucleare - LNL
[f]Istituto Nazionale di Fisica Nucleare - LNS
[g]Riken
[h]Huddersfield University, Queensgate Campus, Huddersfield, HD1 3DH, UK
[i]IceCube Research Center, University of Wisconsin, Madison, Wisconsin 53706
[j]IBA-Research

Design work
By A. Calanna



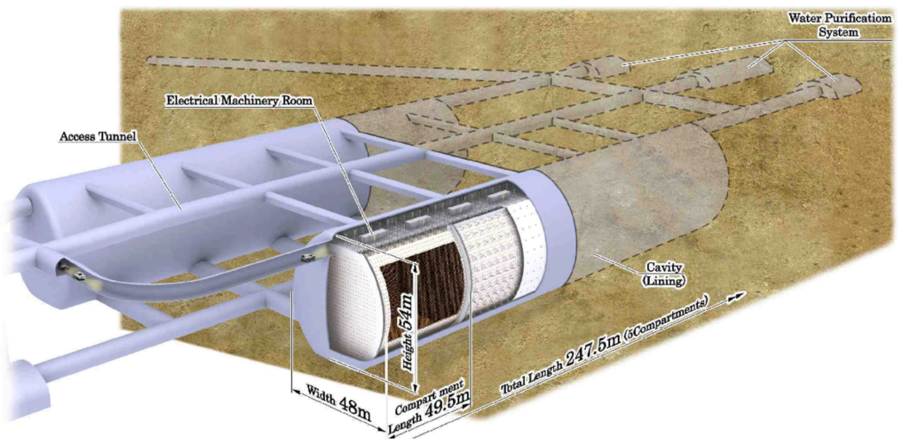


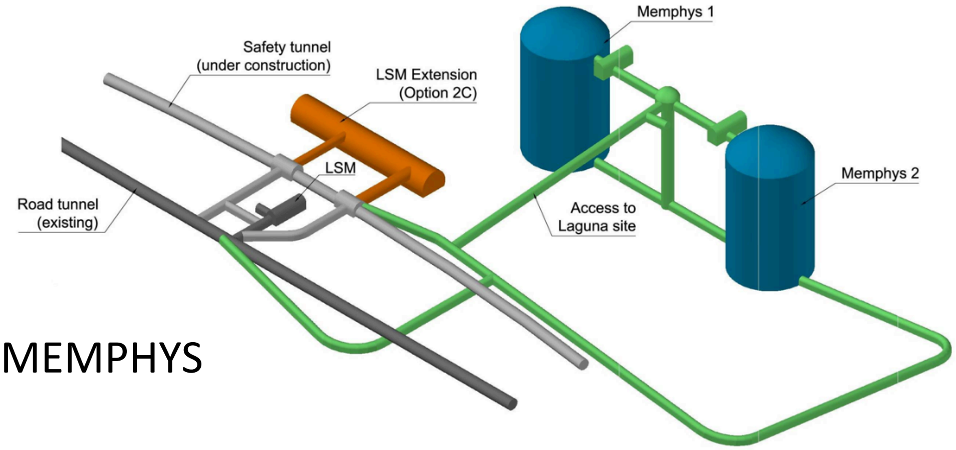


See talk by J. Alonso

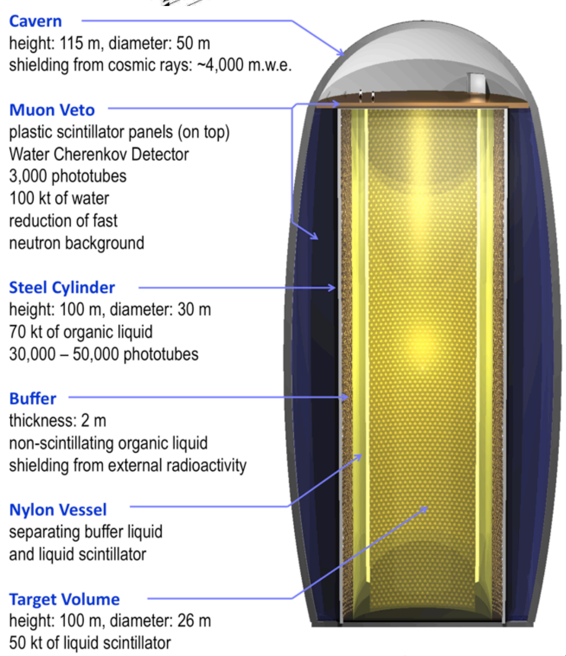
The DAEδALUS Experiment: Detector Options

Hyper-K (or initially, Super-K)





MEMPHYS

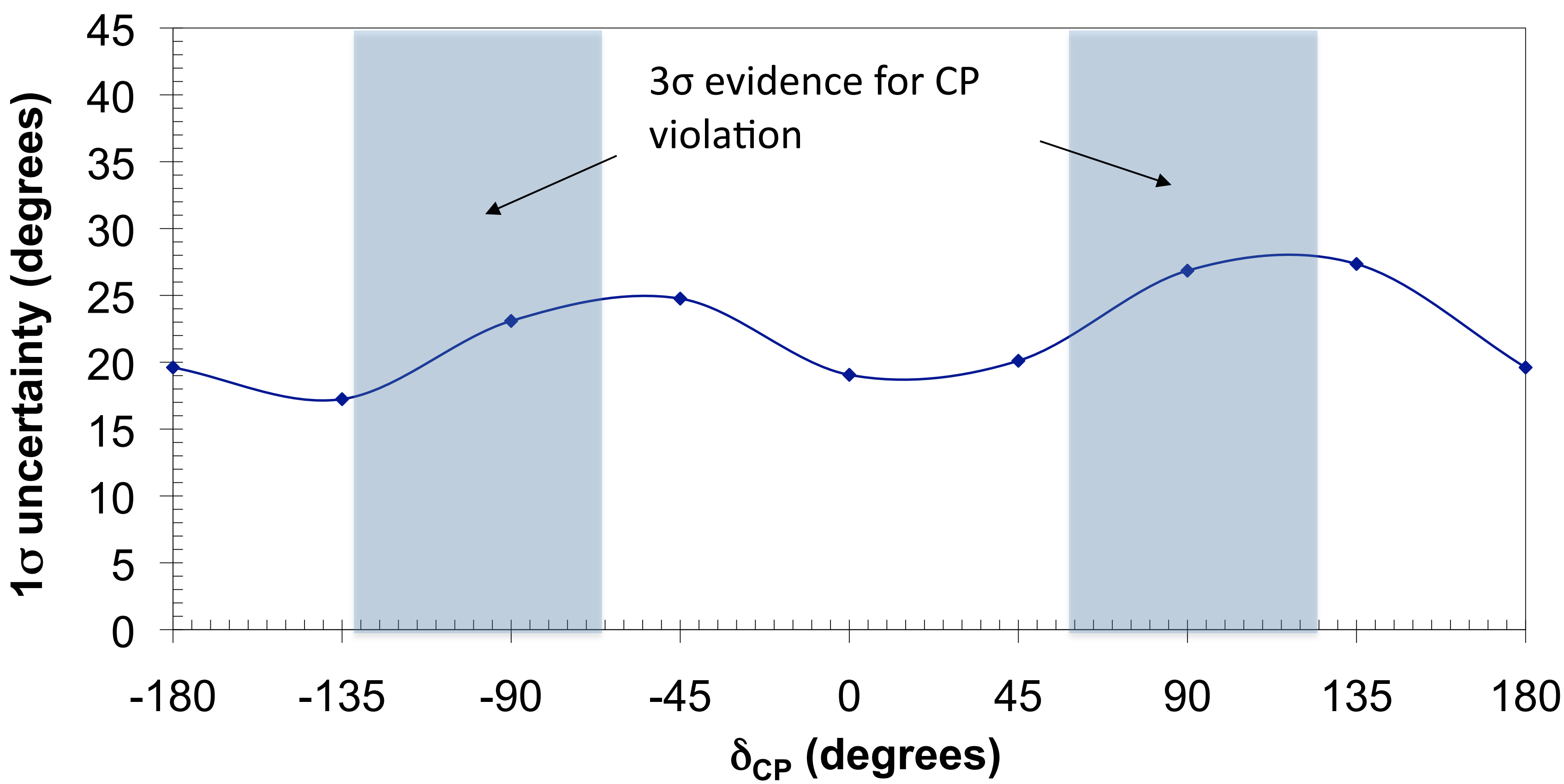


LENA is an outstanding possibility!

Great complementarity to their low energy neutrino astrophysics, (+ solar & geoneutrino) program

The DAEdALUS Experiment: Detector Options

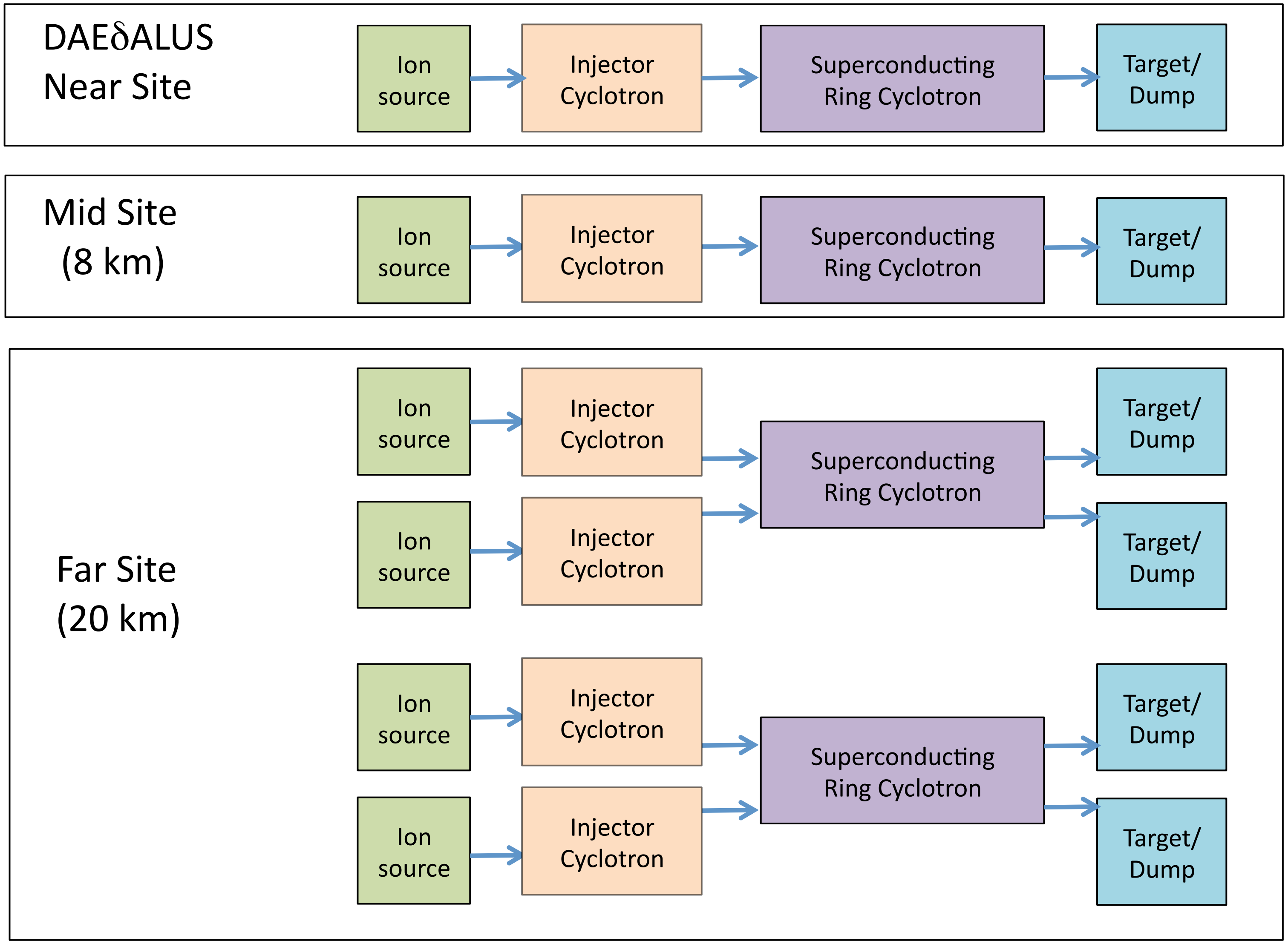
E.g.: Coverage of CP violation parameter at LENA, 10 years



This gets even better if it can be combined with conventional beam measurements!

The DAEdALUS Experiment: Configuration

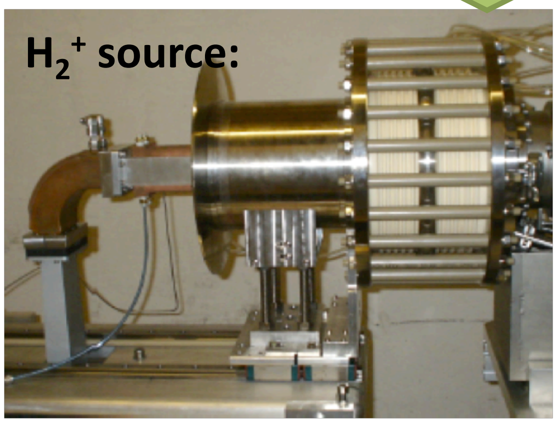
Design Principle: “Plug-and-play” → Allows for multi-phase development plan



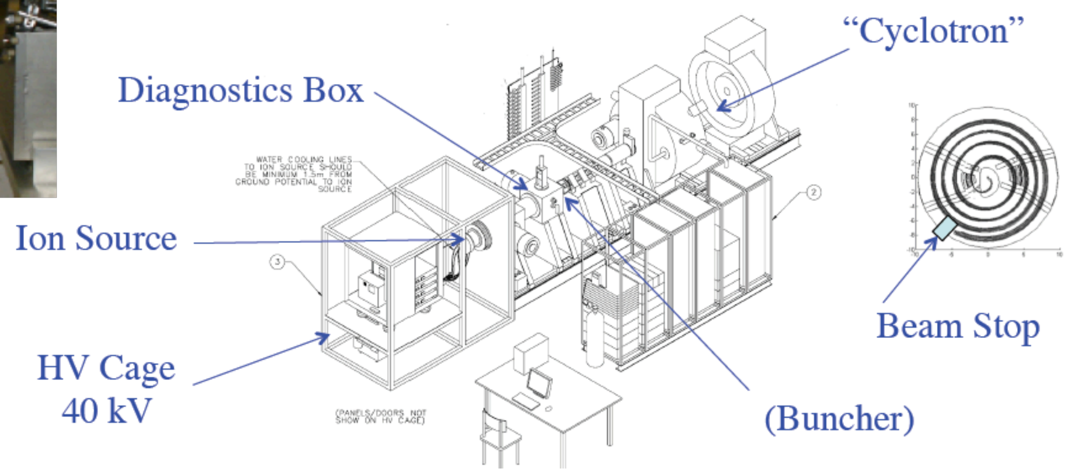
The DAEdALUS Experiment: Multi-phase Development Plan

Phase I: Ion Source

Ion source → Injector Cyclotron → Superconducting Ring Cyclotron → Target/ Dump



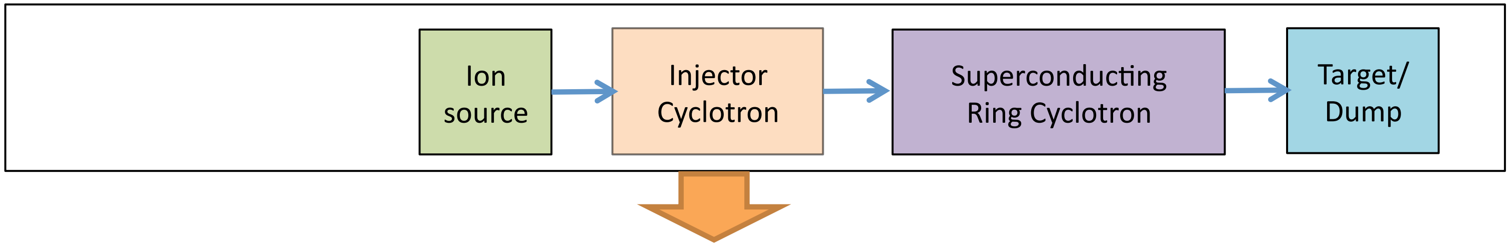
Existing prototype source developed by Collaborators at INFN Catania



Beam undergoing characterization tests at *Best Cyclotrons, Inc.* in Vancouver

The DAEdALUS Experiment: Multi-phase Development Plan

Phase II: Injector Cyclotron

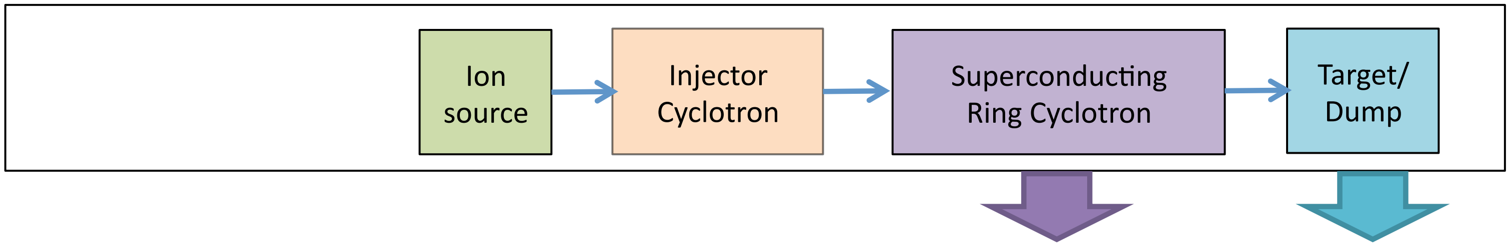


Efforts paired with IsoDAR experiment development:

IsoDAR: Isotope Decay-at-Rest Experiment
to search for sterile neutrino oscillations

The DAEdALUS Experiment: Multi-phase Development Plan

Phases III & IV:



1. Demonstrate & establish the system
2. Reach high-power goals

The DAEdALUS Experiment: Multi-phase Development Plan

Additional Physics Opportunities:

With a new accelerator facility (near, mid), opportunities for new experiments/ additional physics searches:

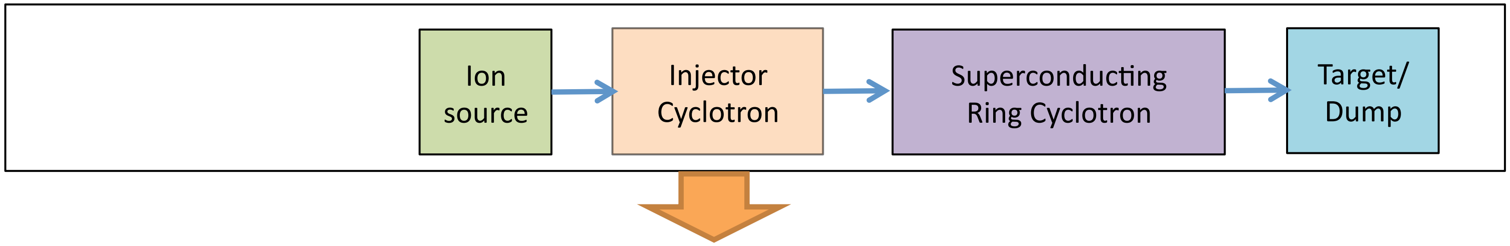
[Contributed ideas:]

- Short-baseline neutrino oscillation waves in ultra-large liquid scintillator detectors
  Agarwalla, S. et. al. JHEP 12 (2011), 85
- Coherent neutrino scattering in dark matter detectors
  Anderson A., et. al. Phys. Rev. D 84, 013008 (2011)
- Active-to-sterile neutrino oscillations with neutral current coherent neutrino scattering
  Anderson, A. et. al. Phys. Rev. D 86, 013004 (2012)
- Measurement of the weak mixing angle with neutrino-electron scattering at low energy
  Agarwalla, S. and P. Huber JHEP 8 (2011), 59

Also, DAEδALUS detector requirements overlap with < 100 MeV physics searches (supernova neutrinos, proton decay, …)

The DAEdALUS Experiment: Multi-phase Development Plan

Phase II: Injector Cyclotron



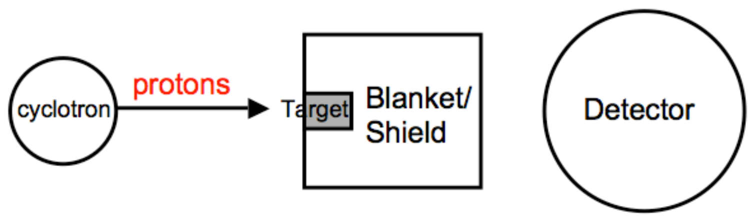
Efforts paired with IsoDAR experiment development:

IsoDAR: Isotope Decay-at-Rest Experiment
to search for sterile neutrino oscillations

The IsoDAR Experiment

Several directions for next generation sterile neutrino search experiments:
• Multi-detector accelerator neutrino beam experiments
• **Very short baseline (VSBL) experiments with compact neutrino sources:**

- High intensity $\bar{\nu}_e$ source using β-decay at rest of ^{8}Li isotope $\Rightarrow$ IsoDAR
- ^{8}Li produced by high intensity (10ma) proton beam from 60 MeV cyclotron
  $\Rightarrow$ being developed as prototype injector for DAEδALUS cyclotron system
- Put a cyclotron-isotope source near one of the large (kton size) liquid scintillator/water detectors such as KAMLAND, SNO+, Borexino, Super-K….



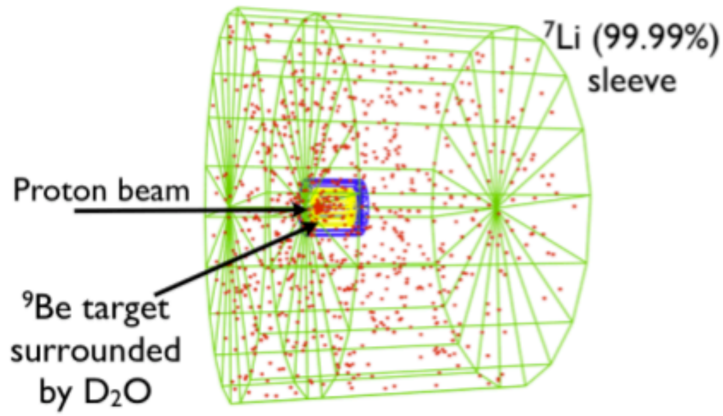
- Physics measurements:
  – $\bar{\nu}_e$ disappearance measurement in the region of the LSND and reactor-neutrino anomalies.
  – Measure oscillatory behavior within the detector.

M. Shaevitz

Phys Rev Lett 109 141802 (2012)
arXiv:1205.4419

The IsoDAR Experiment

- p (60 MeV) + ^{9}Be → ^{8}Li + 2p
  - plus many neutrons since low binding energy
- n + ^{7}Li (shielding) → ^{8}Li
- ^{8}Li → ^{8}Be + e^{-} + $\bar{\nu}_e$
  - Mean $\bar{\nu}_e$ energy = 6.5 MeV
  - 2.6×10^{22} $\bar{\nu}_e$ / yr
- Example detector: Kamland (900 t)
  - Use IBD $\bar{\nu}_e + p \rightarrow e^{+} + n$ process
  - Detector center 16m from source
  - ~160,000 IBD events / yr
  - 60 MeV protons @ 10ma rate
  - Observe changes in the IBD rate as a function of L/E



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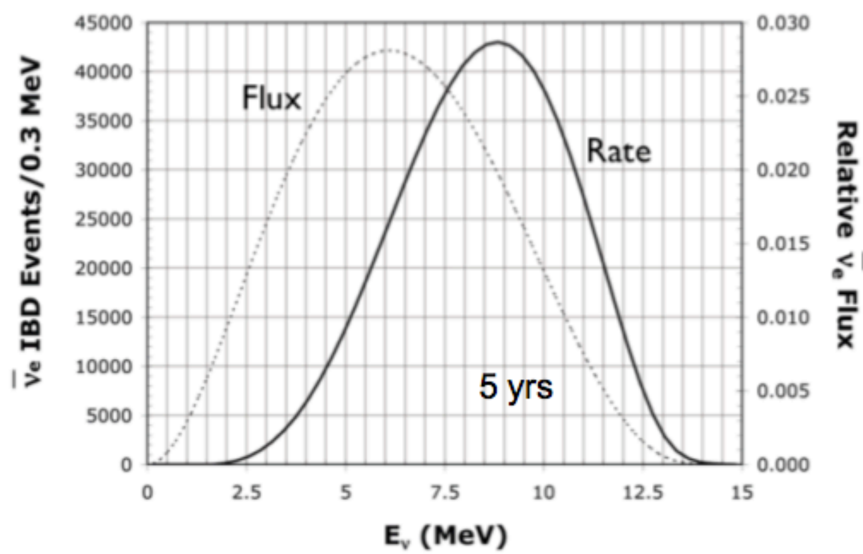

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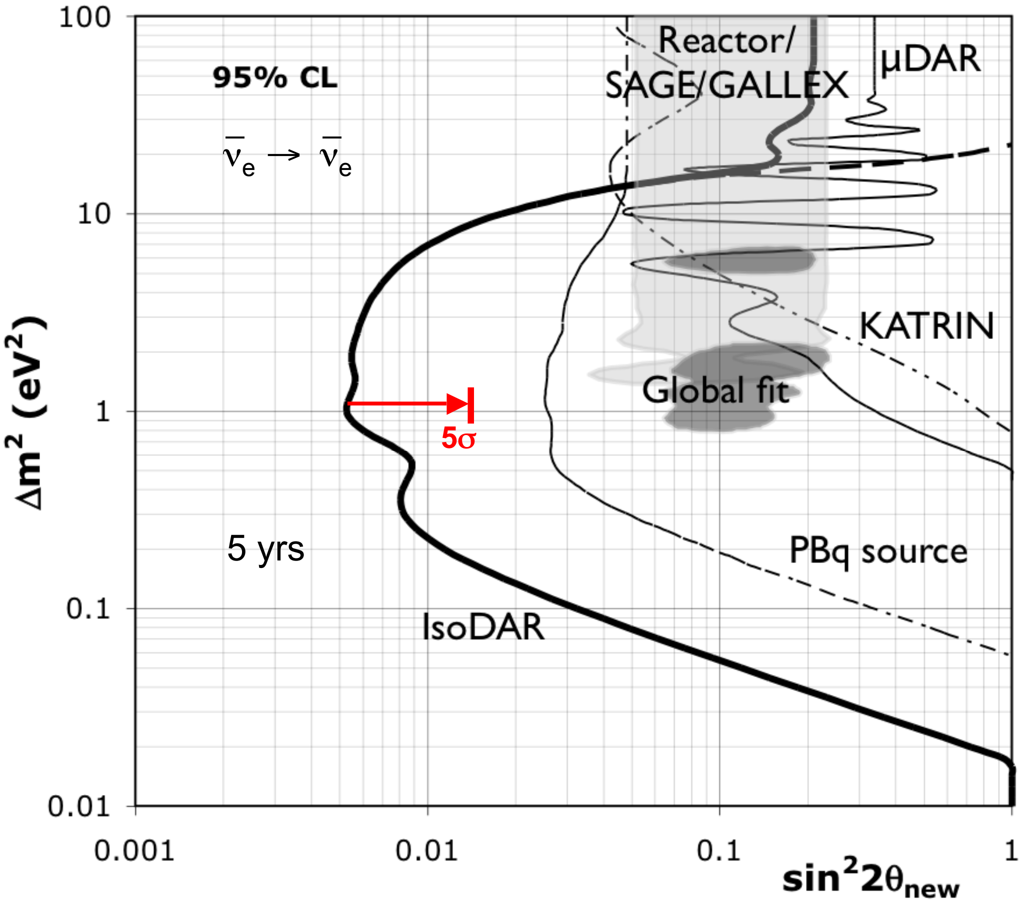
The IsoDAR Experiment

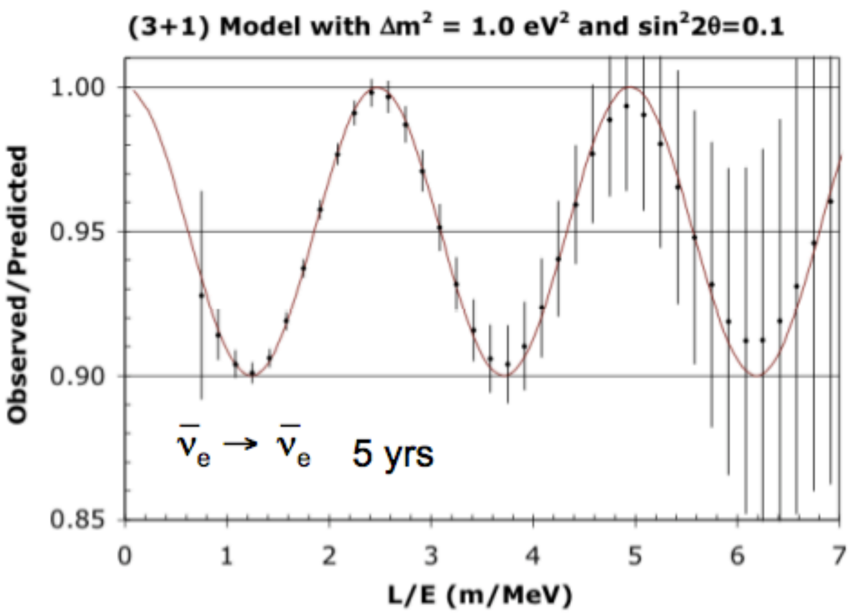
IsoDAR $\bar{\nu}_e$ disappearance oscillation sensitivity (3+1):

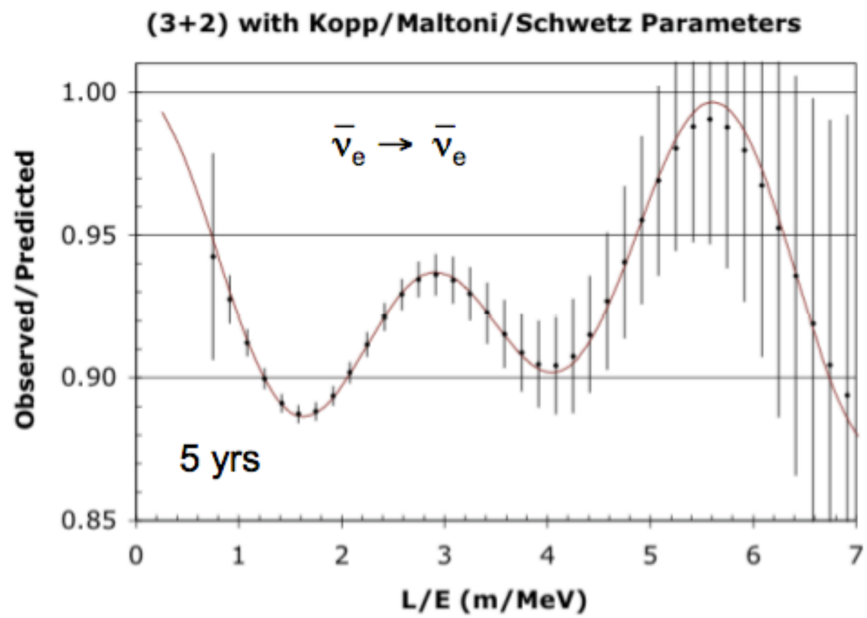


5 σ (discovery) sensitivity to parameters allowed by short-baseline reactor measurements!

The IsoDAR Experiment

Observed/Predicted event ratio vs L/E including energy and position smearing





IsoDAR's high statistics and good L/E resolution has potential to distinguish between simple (left) and more advanced (right) sterile neutrino oscillation models.

M. Shaevitz

Conclusions

The path from IsoDAR$\rightarrow$DAEδALUS,

involving high-power cyclotrons for the production of pion DAR neutrino sources,

provides a strong ongoing R&D program

and a rich physics program which can address urgent neutrino questions, including
  sterile neutrino oscillations (next few years) and
  CP violation in the neutrino sector (next 10+ years),

and provides opportunities for
  neutrino coherent scattering measurements
  weak mixing angle measurements
  and other physics.